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HIGH-TEMPERATURE DIRECT CONVERSION REACTOR "ROMASHKA"

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Introduction

Efficient utilization of nuclear energy in devices designed for various purposes involves search for and development of new ways of energy conversion. Among the installations utilizing nuclear energy of great interest are direct conversion reactors which directly transform thermal energy into electrical in a thermoelectric or thermionic conversion device. One of such devices is "Romashka", an experimental power plant of the Atomic Energy Institute. This installation uses a system which is one of the simplest in the design and most reliable in operation and in which the heat generated in the reactor core is transferred due to thermal conduction into a thermoelectric conversion device mounted on the external surface of the reflector.

The reactor employs fuel elements based on uranium dicarbide which is a promising fuel element material due to its high working temperature and sufficiently high thermal conductivity. The good thermophysical and neutron-physical parameters of the reactor are ensured by the application of metallic beryllium as the reflector material and graphite as the structural material of the core. The application of these materials in the reactor has made it possible the use of a high-temperature conversion device based on silicon-germanium semiconductors.

Description of Direct Conversion Reactor

The nuclear reactor (Fig.1) represents a neutron-physical system operating on fast neutrons. The reactor serves as the source of thermal energy which is converted to electrical energy by of thermoelements.

The heat released as a result of U-235 fission in the reactor core is transferred by conduction radially to the reflector and further, from the lateral surface of the reflector to a semiconductor conversion device mounted coaxially and adjoining the reflector. The reactor has a cylindrical shape, it consists of a core and reflectors (one radial and two end-face) and is positioned vertically.

The reactor core is built up of horizontal fuel elements each of which is made of a graphite body and fuel plates of uranium dicarbide enriched in uranium-235 up to 90 per cent. The total weight of uranium-235 in the core is 49 kg. The radial reflector is made up of coaxially-disposed graphite and beryllium elements. The end-face reflectors are also manufactured of metallic beryllium. Thermal insulation is used to reduce heat leakage at the reactor ends.

The control system of the reactor consists of 4 rods inserted in the radial beryllium reflector, and the lower end-face reflector. Automatic control of the reactor in operation is effected by shifting an automatic control rod made of beryllium and berillia, encased in a heat-resistant steel jacket and inserted in the radial reflector. Manual control of the reactor is accomplished by shifting a manual control rod inserted in the radial reflector. The latter rod is a combination of a scattering section based on beryllium and berillia, and an absorbing section based on a boron-containing alloy. The temperature effect is offset by displacing the lower end-face reflector. The scram system of the reactor consists of two safety rods inserted in the radial reflector, and of the lower end-face reflector. The safety rods are similar in design to the manual control rod. All the controls, with

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the exception of the automatic control rod, are driven through a hydraulic system. The automatic control rod is shifted by an electrical servo drive. The control and safety element drives are mounted underneath the reactor vessel.

The functions of a thermoelectrical conversion device are performed by conversion device based on a silicon-germanium alloy. The each thermoelectric pair is made up of n - and p-type thermoelectric elements connected by a switch plate on the hot side. On the cold side, separate thermoelectric pairs are switch-connected into a single circuit. In all, the thermoelectrical conversion device of the installation is divided into 4 groups of thermoelements, each of which has independent terminals. Thus the conversion device design enables carrying out investigations on the characteristics of both individual groups and the entire device as a whole when the groups are connected either in series or in parallel. Inside each of the four groups of the conversion device the thermoelements are switch-connected in series into four parallel circuits. The general view of the conversion device is presented in Fig.2.

The basic parameters of the direct conversion reactor are listed in the Table.

Experimental Investigations and Theoretical Calculations Substantiating the Selection of the Installation Parameters

The power potentialities of a direct conversion reactor without a coolant are determined by the ultimate characteristics of the materials used, the size of the basic reactor components and their design. The intimate interrelationship of these parameters necessitated extensive theoretical calculations as well as experimental investigations on thermophysical and neutron-physical phenomena, and the reactor materials with a view to finding the optimum characteristics of the installation and substantiating the operability of its components.

Thermal Energy Calculations

The electrical power of the installation is, in the final analysis, determined by the thermal conditions in the converter,

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the parameters of its design and the physical properties of the materials. The expression describing the value of electrical power may be represented thus:

$$W = \frac{M}{(1+M)^2} \frac{1 - \frac{r_k \cdot S}{l(\rho_1+\rho_2)} - \frac{2\varkappa_3 S_3}{S(\varkappa_1+\varkappa_2)}}{1 + \frac{2Q_0 l \alpha^2 \left[\frac{1}{M+1} \cdot \frac{T_r}{T_r - T_x} - \frac{1}{2} \frac{1}{(M+1)^2}\right]}{n \cdot m \cdot S(\rho_1+\rho_2)(\varkappa_1+\varkappa_2)}} \cdot \frac{\sum_{i=1}^{n_3} \sum_{k=1}^{n_3} \alpha_i \alpha_k Q_i Q_k}{(\varkappa_1+\varkappa_2)^2 \frac{S}{m} \sum_i n_i (\rho_{1i}+\rho_{2i})}$$

where Q_i = heat flow through the i-th zone,

Q_c = total heat flow throught the converter,

$\varkappa$ = thermal conductivity coefficient,

ρ = specific resistance,

α = thermoelectromotive force coefficient

l = length of a thermopile,

S = thermopile cross-section area,

S_3 = cross-section area of thermal insulation between piles,

n_s - number of zone,

n = number of series-connected pairs,

m = number of parallel-connected pairs,

T_h, T_c = temperature of hot and cold junctions of semiconductors,

r_k = switching resistance of one thermoelectric pair

M = ratio of external load resistance to conversion device internal resistance.

(Superscripts 1 and 2 refer to semiconductor materials of the n- and p-type; i or k are zone numbers).

The non-uniformity in the distribution of temperatures and heat flows over the external surface of the radial reflector is described in this formula approximately, by dividing the conversion device into annular zones along the height, the temperature conditions within the zones being assumed identical. The influence of the non-uniformity on the Joule and Peltier effects is neglected.

The specific feature of the installation is the fact that the operating conditions of the conversion device and hence its electric output are determined by the permissible temperature level of the individual components of the reactor and the conversion device as well as by the possibilities of heat removal by the radiator. In this connection, to determine the power para-

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meters of the installation, it was necessary to carry out thermal calculation of the direct conversion reactor as a whole.

The problem of temperature distribution in the core, the reflector and the conversion device amounts to solving thermal conductivity equations for a multiregion system with non-linear boundary conditions, which describe heat transfer by radiation. Numerical solution of these equations was accomplished on an electronic computer. The temperature distribution in the radial reflector for one set of operating conditions is shown in Fig.3.

The core components are under strained conditions both as regardsgards the temperature levels and the temperature drops which determining thermal stresses. In this connection the problem was solved concerning the influence of a possible fuel element breakdown on the temperature rise in the core. The solution was accomplished by the method of electrical simulation of temperature fields on electroconducting paper.

In the system under review, the removal of heat which has passed through the conversion device is effected by radiation. The maximum heat removal from the surface at a predetermined **average** temperature of the cold layers of the conversion device ensures the highest possible electrical output, other things being equal. With the aim of finding the optimum shape of the radiating surface (the number of fins, the size, the profile), a set of integral **differential** equations was solved, these equations describing the temperature distribution in the fins, taking into account the mutual irradiation of the elements, as well as heat conductivity.Fig.4 demonstrates the dependence of heat removal on the weight and number of the fins.

Using the results of thermal calculations of the system, determination was made of the installation electrical output as a function of the thermal power passing through the conversion device under conditions of varying figure of **merit** thermoelectric element.

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Neutron-Physical Calculations

The neutron-physical characteristics of the reactor were calculated on an electronic computer using the multigroup method of statistical tests (the Monte-Carlo method). In this case, the application of this method made it possible to effectively take into account the geometrical and physical features of the sistem associated with the heterogeneous structure of the core, the presence of complex shaped channels and clearances, drastically non-uniform physical properties of the core and reflector materials, the specific reactor control system, etc. In calculations, use was made of a multigroup (2I-group) system of constants which takes into consideration the resonance structure of the U-238 cross-section, the (n,2n) reaction on beryllium and inelastic transitions in the first nine groups. About 50,000 neutron histories were traced in the course of calculation.

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Experimental Study of Characteristics of Installation Components

For the purpose of substantiating the parameters built into the installation, experimental thermophysical and metallophysical investigations of the installation materials and assemblies were carried out.

Investigated were the contact interaction between uranium dicarbide and graphite, evaporability of uranium dicarbide in an inert medium and in a vacuum at temperatures of up to 2,000°C (Fig.5). The temperature dependence of the coefficient of linear expansion and the coefficient of thermal conductivity of uranium dicarbide over a wide range of temperatures (Fig.6) was studied. These investigations, alongside the investigations into the thermal strength characteristics of uranium dicarbide, testing of mock-up fuel elements and loop testing of uranium dicarbide specimens demonstrated the operability of the fuel elements under operating conditions.

The use in the reactor of a beryllium reflector operating at high heat flows in the range of temperatures close to the melting point, called for experimental investigation into the interaction of metallic beryllium with various structural materials, a study of the coefficient of thermal conductivity of beryllium, the deformability and thermal stability of beryllium.

To reduce heat leakages at the reactor ends and between the elements of the thermoelectrical conversion device the installation uses high-temperature thermal insulation. In this connection, the heat conductivity of the thermal insulation in various media in the region of working temperatures was studied.

One of the important aspects of the investigations carried out was a study of the operability of the thermoelectric elements of the conversion device in neutron and gamma fluxes. Repeated tests of thermoelectric elements in the loops of the RFT reactor at integral neutron fluxes of 3×10^{19} th.n./cm^2 lasting for many hours enabled us to conclude that the variation in the basic properties of the thermoelectrical elements was within permissible limits (Fig.7).

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Stand Investigations of Neutron-Physical and Thermal Energy Characteristics of the Installation

Investigation of Neutron-Physical Characteristics

Five different assemblies were made which differed in the concentration of fissionable material. Comprehensive investigations were carried out on each assembly, and the problems studied included the dependence of critical charges on the core composition, the efficiency of the reflectors and the controls, the distribution of heat release in the core, the effect of design clearances on reactivity, etc.

Much attention was given to studying the effect of the displacements of the lower end-face reflector and shaping of the core to meet the neutron-physical characteristics of the reactor system, and also to ascertaining the differential efficiencies of the control rods and the heat release fields. Some of the results obtained are presented in Fig.8 depicting the distribution of heat release along the radius and the height of the core. In all these cases, reactivity was measured in different ways: by the rising period, pulse and integral methods.

A comparison of the results of the reactivity measurements by different methods permitted evaluation of the efficiency of photoneutrons delayed owing to the beryllium reflector. It has been established that reactors of this type contain practically no photoneutrons, and experimental data may be processed with the aid of the characteristics of six groups of delayed neutrons.

Investigation of Thermal Energy Characteristics

The final stage of the reactor test on a full-size testing stand was preceded by integrated tests of a full-scale thermal model of a reactor on an electrically heated stand.

The above-mentioned tests were to verify the operability of the entire installation as a whole and of its individual assemblies, as well as to determine the installation working parameters under stationary and non-stationary conditions.

In the course of the test, the temperature fields of the various components of the installation were measured continuously. For

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this purpose, 53 tungsten-rhenium and 86 chromelalumel thermocouples were inserted in the reactor and the conversion device.

The electrical characteristics of the conversion device were measured by means of a special electrical panel which enabled the following operations to be performed:

a) smooth variation of the load from 0.1 to 10 ohms for each of the four thermoelectric element groups, and measuring the emf, the short-circuit current, the operating current and voltage;

b) electrical measurements, not only separately for individual groups, but also with series and parallel connection of the groups.

The electrical output of the conversion device was determined at maximum power. The installation was tested under nominal conditions for over 1,000 hrs.

An analysis of the results of the tests of the installation pointed to good operability of all the basic components of the direct conversion reactor. The installation exhibited sufficiently stable characteristics throught the test period. During practically the entire test the thermo-emf of the conversion device remained constant. Towards the end of the tests some increase in the internal resistance of the conversion device was noted as a result of which the electrical output picked up from the conversion device (at maximum power) fell off by 10 per cent on the average.

The tests conducted made it possible to study and demonstrate the operability of the core, the reflector and the conversion device under operating conditions.

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BASIC PARAMETERS OF DIRECT CONVERSION REACTOR

1. Thermal Energy Parameters of Installation

No.	Parameter	Value
1.	Electrical output, kW	0.50–0.80*)
2.	Total thermal power, kW	40**)
3.	Maximum temperature of beryllium reflector, °C	1,200
4.	Maximum temperature of external surface of beryllium reflector, °C	980
5.	Average temperature of bases of radiating fins, °C	550
6.	Maximum temperature of uranium dicarbide fuel elements, °C	1,900

2. Neutron-Physical Characteristics of Reactor

No.	Parameter	Value
1.	Charge of uranium-235, kg	49
2.	Efficiency of automatic control rod, %	0.2
	Efficiency of manual control rod, %	0.4
3.	Efficiency of safety rod, %	0.4
4.	Efficiency of all control rods, %	1.4
5.	Efficiency of mobile end-face reflector, %	3.5
6.	Total neutron flux in core centre, n/cm^2sec.	10^{13}
7.	Total neutron flux at reactor core boundary, n/cm^2sec.	$7x10^{12}$
8.	Neutron leakage from reactor, n/cm^2sec	$3x10^{11}$

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*) Depending on temperature conditions

**) Taking account of leakages

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Fig.1. General view of the reactor

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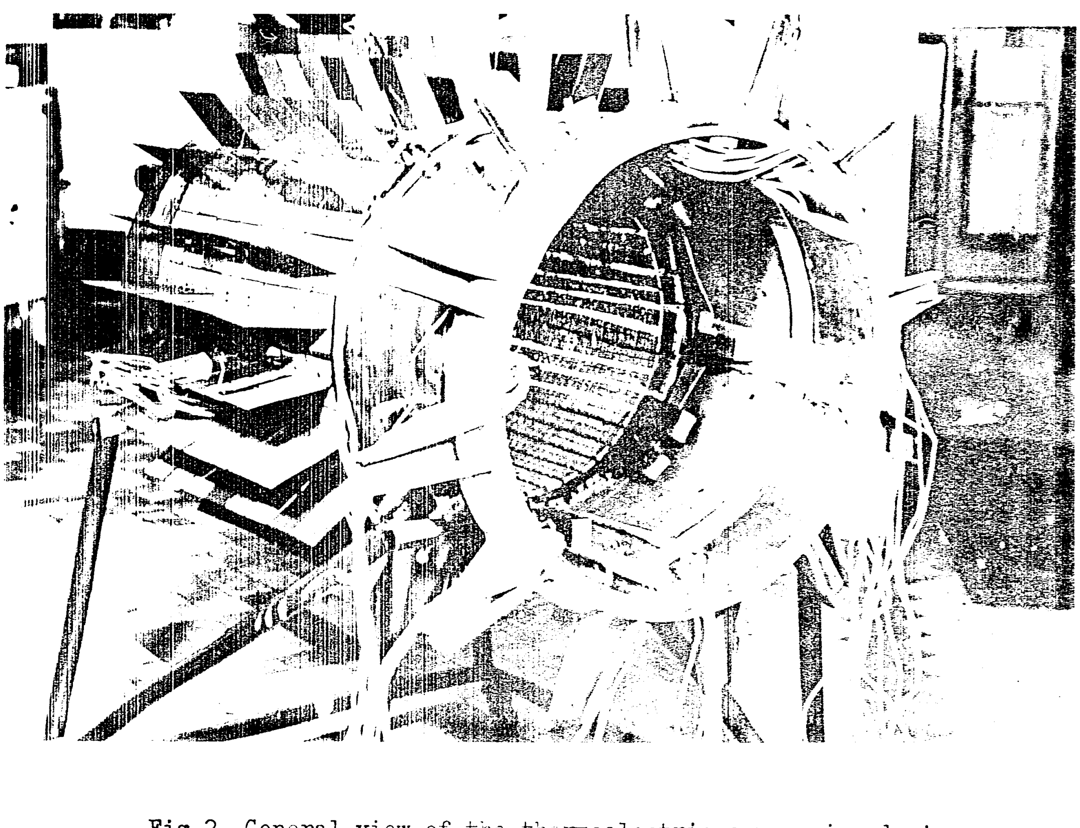

Fig.2. General view of the thermoelectric conversion device.

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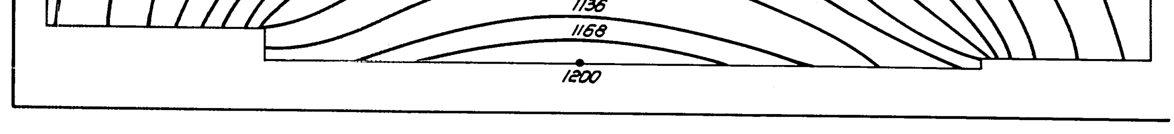

Fig.3. Temperature distribution throughout the cross-section of the radial **reflector**.

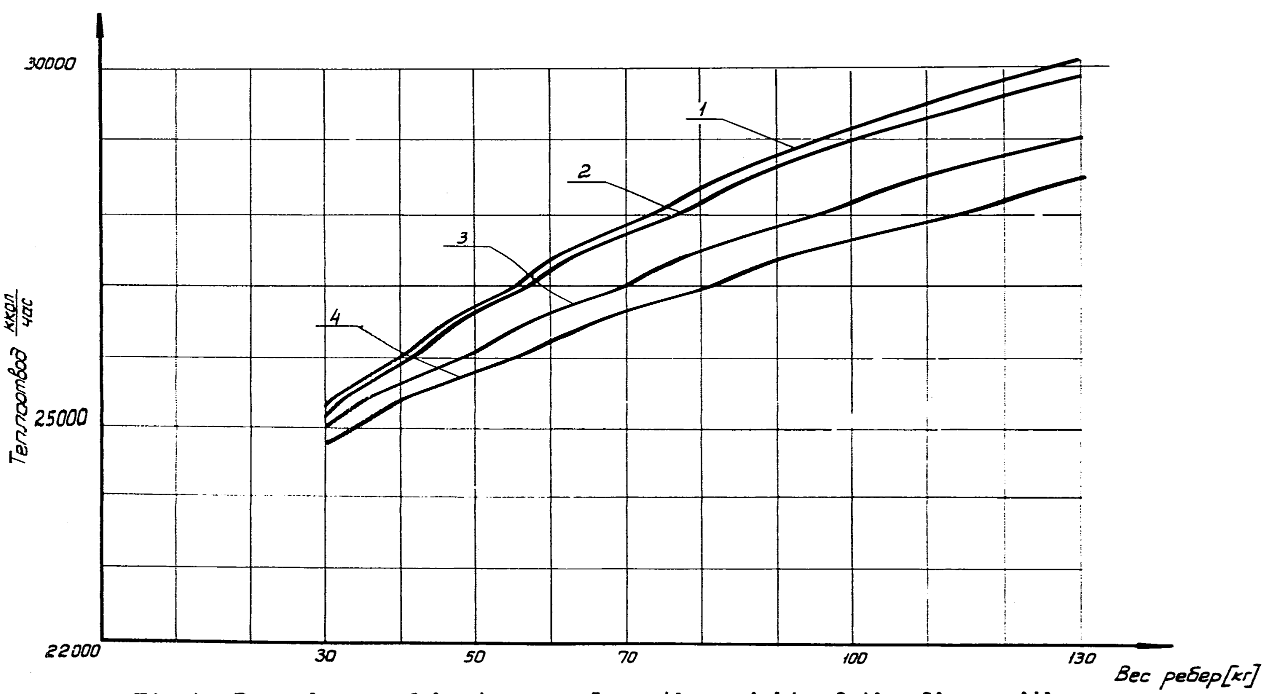

Fig.4. Dependence of heat removal on the weight of the fins, with different numbers of fins (temperature of the fin base, 600°C): 1-6 fins; 2-9 fins; 3-18 fins; 4-36 fins.

A. Heat removal $\frac{\text{kcal}}{\text{hr}}$; B. Fin weight,kg.

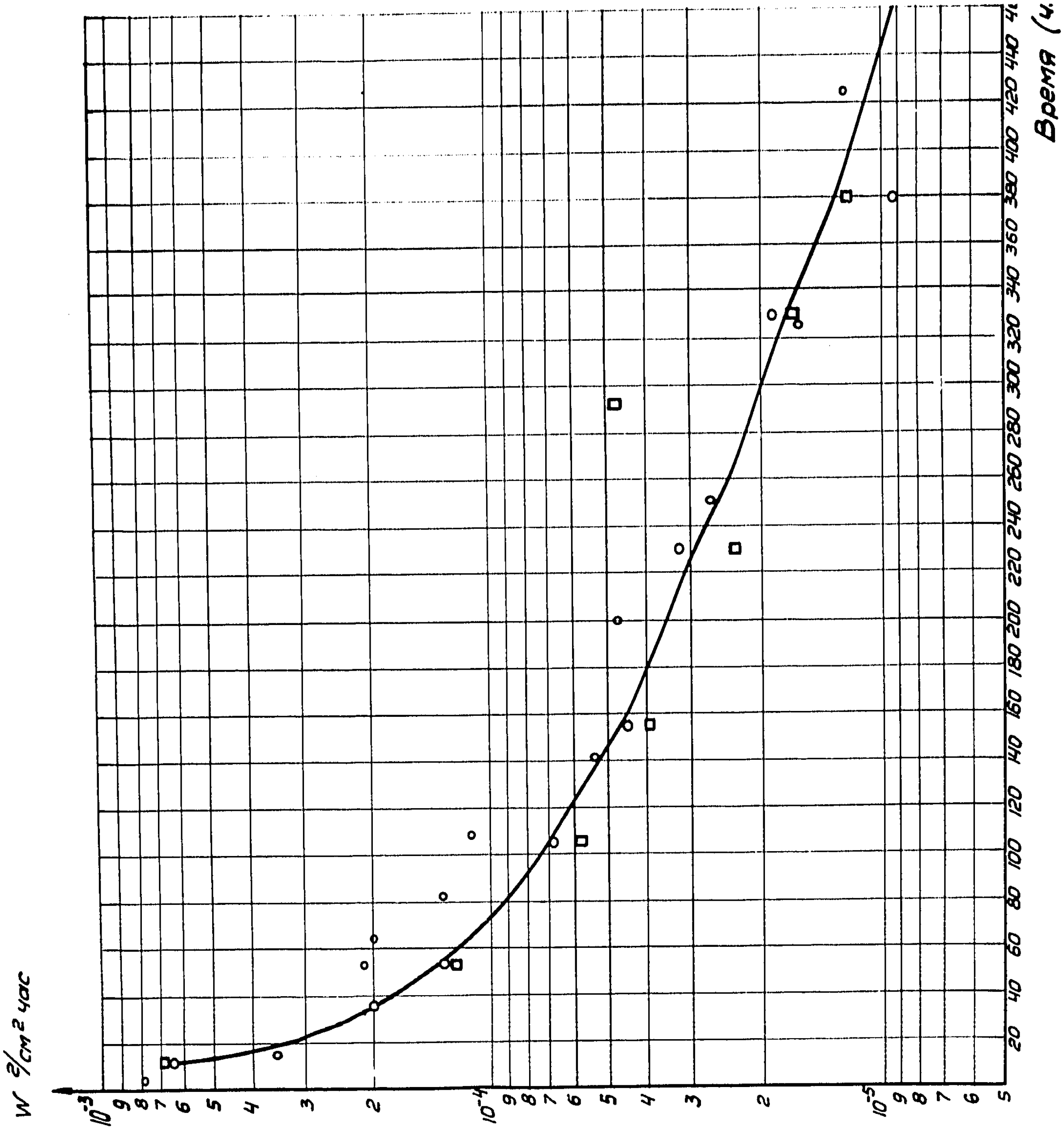

Fig.5. Rate of evaporation of uranium dicarbide in an inert medium at $t=2,000^{\circ}C$

W, gr/cm^{2}hr   Time, hr

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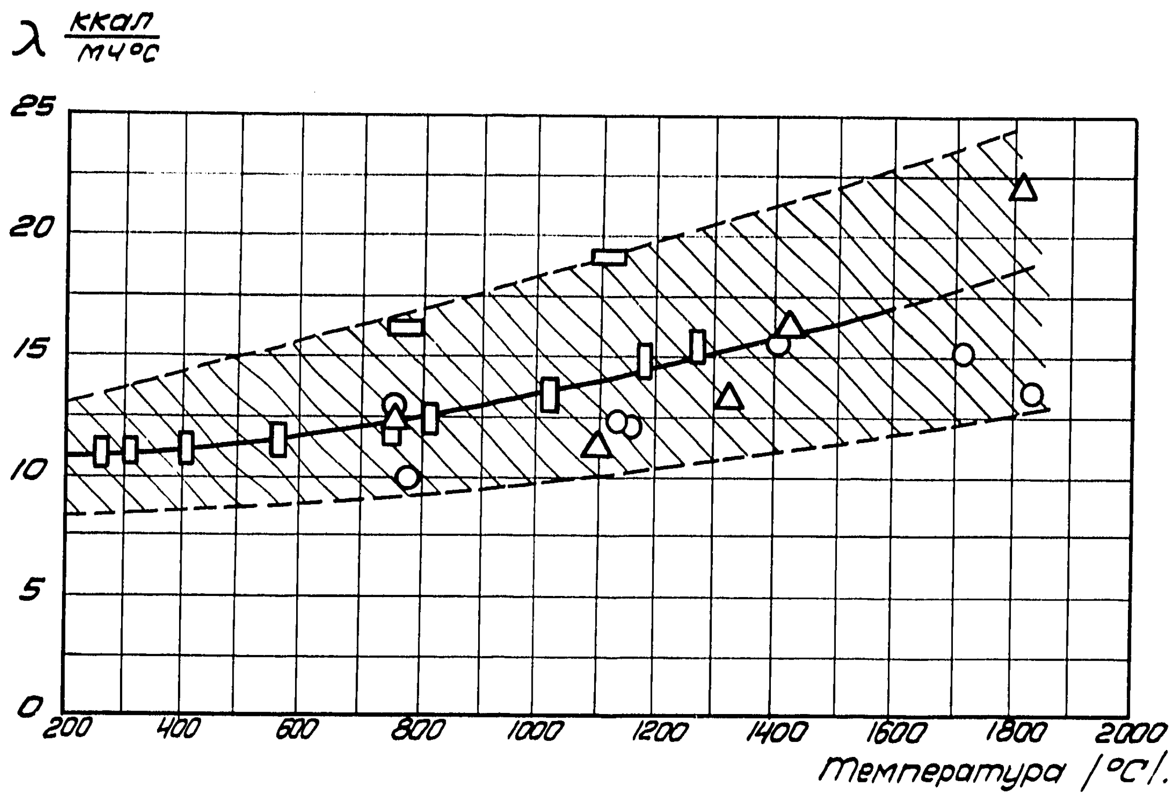

Fig.6. Dependence of heat conductivity of uranium dicarbide on temperature

λ, kcal/m hr $^{\circ}$C temperature ($^{\circ}$C)

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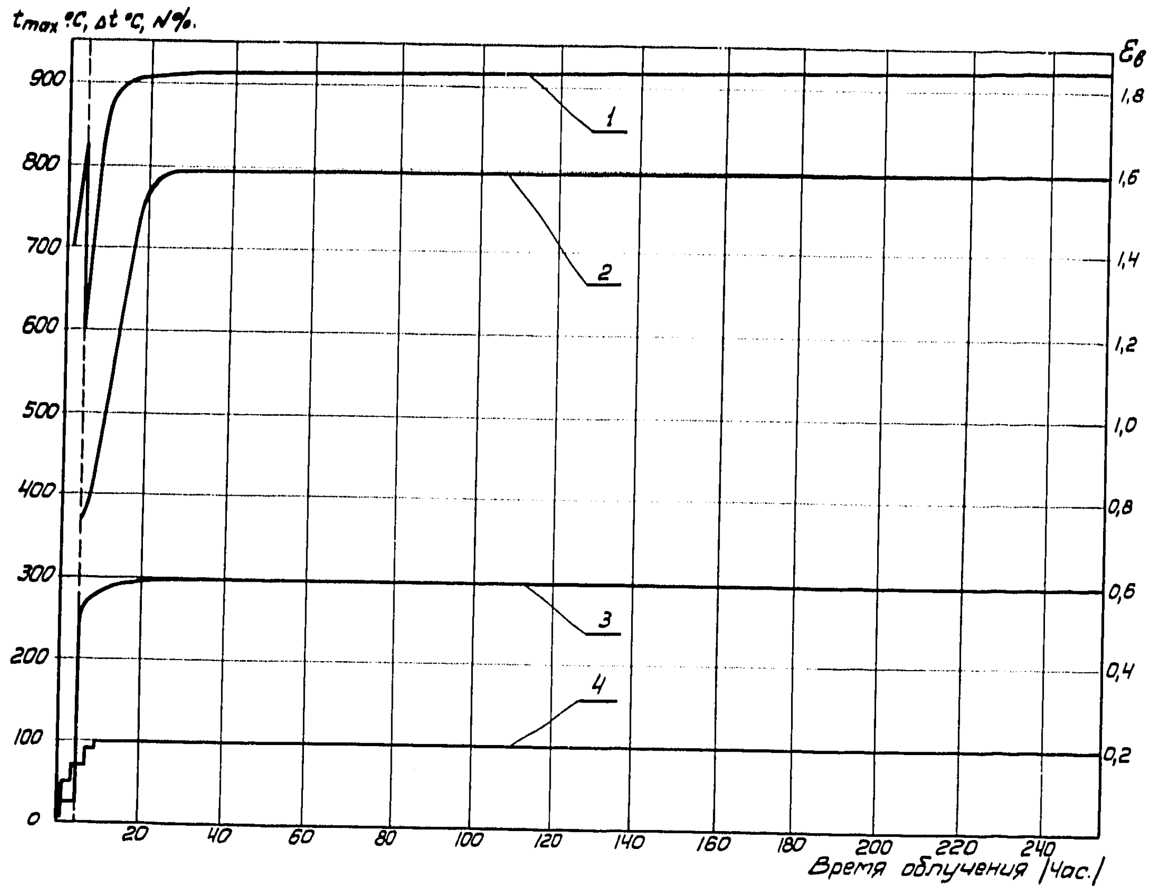

Fig.7. Variation of the basic parameters of semiconductor thermo-elements in the course of reactor irradiation:
1–temperature of the hot junction; 2–thermo-emf of the section;3–temperature drop on thermoelements;4–reactor output.
Maximum integral neutron flux–abt.3×10^{19} n/cm^2.

Irradiation time,hr

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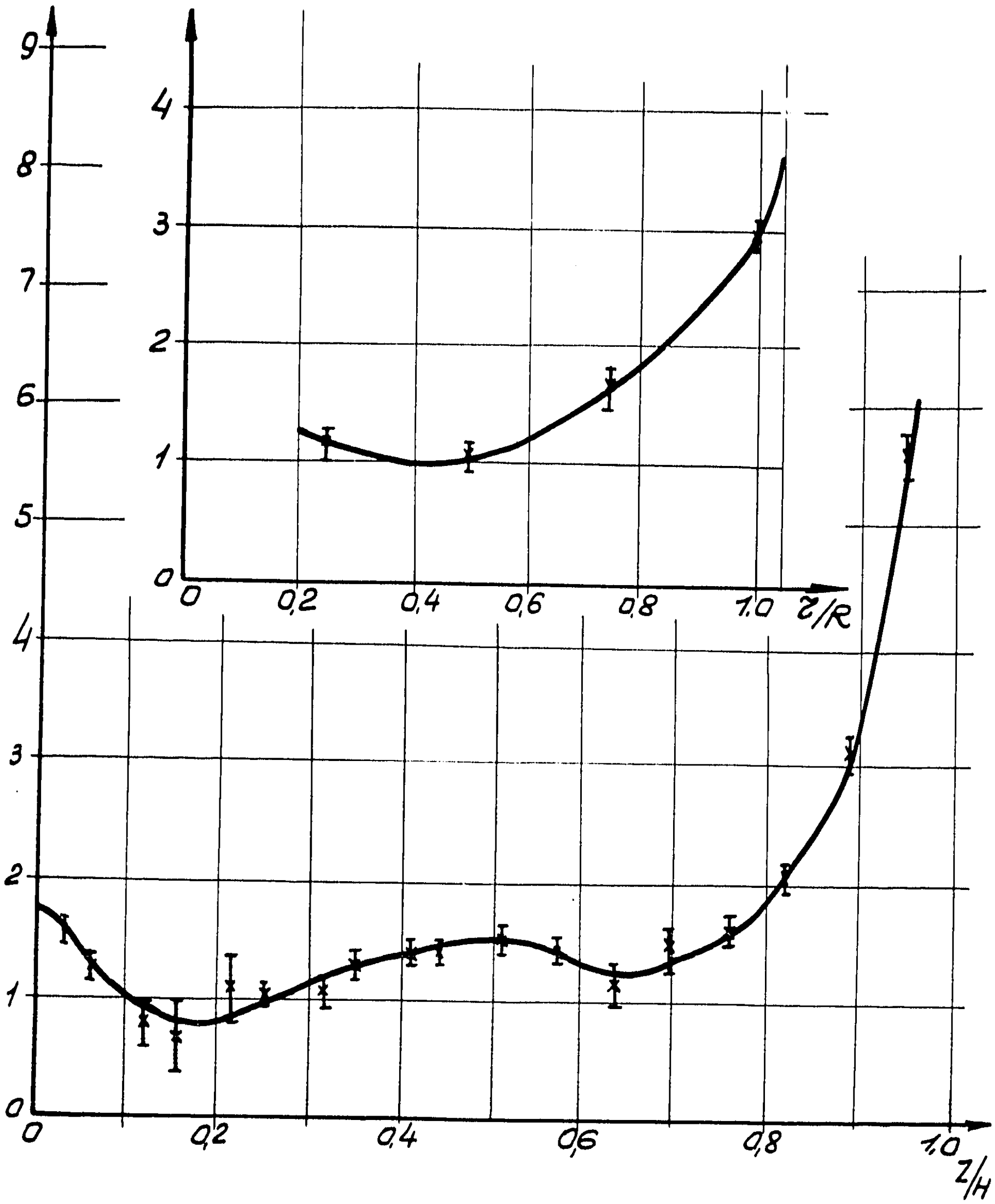

Fig.8. Relative distribution of heat release along the height and the radius of the core.

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